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On the feasibility of real time imaging in radiotherapy using antiproton beams

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I. Kantemiris,[a,1] **P. Karaiskos,**[b] **E. Georgiou,**[b] **A. Angelopoulos,**[a] **N. Giokaris,**[a,c]
S. Dubnicka,[d] **M. Fulop**[e] **and T.E. Kalogeropoulos**[a]

[a]*Nuclear and Particle Section, Physics Department, University of Athens,*
Panepistimioupolis, Ilissia 157-71 Athens, Greece
[b]*Medical Physics Department, Medical School, University of Athens,*
75 Mikras Asias, 115-27 Athens, Greece
[c]*Institute of Accelerating systems & Applications, Panepistimioupolis, Ilissia 172-14 Athens, Greece*
[d]*Institute of Physics, Slovak Academy of Sciences, Bratislava, Slovak Republic*
[e]*Institute of Preventive and Clinical Medicine, Slovak Health University, Bratislava, Slovak Republic*

E-mail: ikantem@phys.uoa.gr

ABSTRACT: Antiprotons whose potential in clinical applications has not yet been fully studied and explored, interact in a way similar to the widely used protons. The great advantage of antiprotons over protons is that at the end of their path annihilate and release about 1.88GeV more energy. Although many particles are produced by annihilation most of them escape from the target. Detecting a portion of these particles during patient's irradiation would offer the possibility to monitor the beam in the target in real time. In the current work we investigate the feasibility of real time imaging during radiotherapy by using antiproton beam. In this study a prostate case is simulated using one field and given a typical dose fraction of 2Gy to the target. Monte Carlo code is used to calculate the energy spectrum of the most prominent particles that escape from the target which could be detected outside the patient, as well as the degree of scattering of these particles, as an indication of merit for their use in order to produce an image which represents the absorption of the beam in the target. Results based on these criteria suggest that real time imaging is possible by detecting either charged pions or photons which mainly come from π^0 decays or e^+e^- annihilation.

KEYWORDS: Medical-image reconstruction methods and algorithms, computer-aided so, Image reconstruction in medical imaging

[1]Corresponding author.

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Contents

1 Introduction

The high acceptance of heavy charged particles and ion beams in cancer treatment, is attributed both to the excellent dose conformality of target's dose and the sparing irradiation of the healthy tissue (due to the formation of Bragg peak). Almost all long lived and stable particles such as charged pions and protons just like ions (up to oxygen) have been tested in clinical applications. However antiprotons have not yet been tested. The idea of using antiprotons in clinical applications goes back to 1984 and 1989 when L.Gray et al. [1] proposed antiprotons for radiotherapy and T.Kalogeropoulos et al. [2] proposed them for imaging. The scientific interest in the use of antiproton beam for radiotherapy was recently been renewed owing both to their advantageous dosimetric characteristics (the published results about their Relative Biological Effectiveness (RBE) in M H Holzscheiter et al. [3] are very promising) and the potential they offer for real time imaging. In this study we investigate the feasibility of real-time imaging during radiotherapy by calculating the energy spectrums.

2 Materials and methods

In order to study the energy spectrums of the secondary particles produced by antiproton annihilation, the irradiation of a prostate is simulated. Hence a water phantom of 20x20x20cm^3 with a centered target is irradiated with one square of 4x4cm^2 field (figure 1). An energy spectrum of antiprotons (100-120MeV) is used in order to spread out the Bragg peak and deliver full dose to the whole volume of prostate. A typical dose fraction of 2Gy is delivered to the target. The simulation package implemented is FLUKA 2006.3b [4, 5].

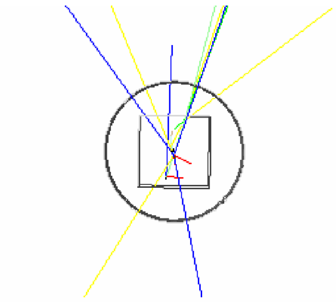

Figure 1. Simulation's procedure. In the middle of the figure there is a water phantom (20x20x20cm^3) and the surrounding ring is a detector. The beam goes towards page's plane and phantom's center. The lines which come out from annihilation's vertex represent secondary particles which are being produced by this annihilation. Some of these particles escape the water phantom and cross the detector. SimpleGeo 3.0 [6] is implemented for this figure.

Table 1. Percentage of non-scattering photons which travel 10cm in water in order to escape the water phantom.

E (MeV)	% Non-scatter
0.5	38
1	49.3
10	80.1
100	84.1
1000	81.7

3 Results

3.1 Photons

Many photons are produced by antiproton's annihilation and secondary interactions. The most significant interaction which produces photons, is the π^0 decay. Neutral pions have short life time ($\sim 10^{-16}$s) and practically decay at the point where they were produced. Figure 2 presents energy spectrum of photons which manage to escape the water phantom. The photons shown in the figure are those produced by π^0 decay, escape from the water phantom and thus are subject to detection by an appropriate detector, as well as those produced in the phantom by any possible interaction. For the energy range of photons in figure 2, also the percentage of non-scattering photons, which could be used to monitor the radiation beam, is calculated (table I). In order to extract table I, the formula: $100 \cdot e^{-(\mu_{total}/\rho) \cdot x}$ is used, where μ_{total} takes into account coherent and incoherent scattering, photoelectric absorption and pair production [7]. It is assumed that all the photons are generated at the center of the phantom and have to travel a distance of 10cm in order to escape the water phantom.

Table I points out that photons with energy higher than 10MeV do not scatter significantly (in mean 20% is scattered). Furthermore the amount of these photons is very high and are generated in 4π geometry, so by detecting a part of them imaging should be feasible. The region of the energy

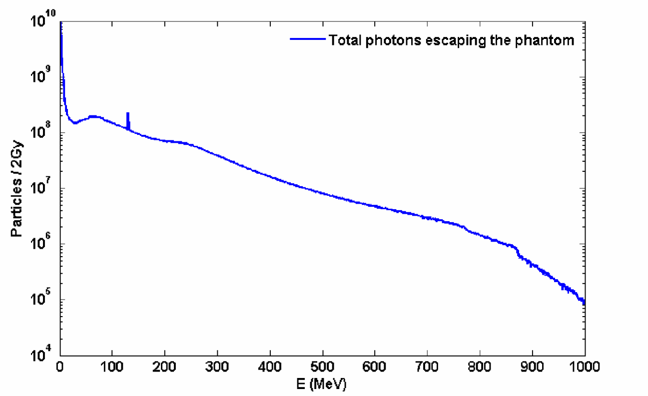

Figure 2. Energy spectrum of the photons which escape the phantom. The spectrum goes up to 1GeV. An enormous amount of photons is produced and escape the phantom when a 2Gy dose is delivered to the target. Photons with energy higher than 10MeV (except near the energy area of 130MeV) could be used for imaging, because only 20% of these photons scatter and produce noise to our image.

spectrum around 130MeV should be excluded for imaging because, the peak shown in figure 2 is formed by the interactions of charged pions with neutrons or protons in the phantom as shown in (1). These interactions may take place away from the target and therefore their detection is meaningless in regards to imaging.

$$\pi^+ n \rightarrow p\gamma \qquad \text{and} \qquad \pi^- p \rightarrow n\gamma \tag{3.1}$$

Antiproton annihilation produce many residual nuclei which are formed in excited state. Their kinetic energy is in few MeV range, so they don't move away from the place where they were produced. Some of these nuclei deexcite by emitting positrons (beta+) which annihilate near their production region. Figure 3 presents the energy spectrum of photons with energy up to 10MeV. The 511keV peak is prominent in figure 3 and thus imaging should be feasible by detecting these photons which are produced by positron annihilation. However the mean half life of some of the most prominent residual nuclei is quite high (few tenths of sec) and thus a time delayed imaging may occur instead of real time imaging.

Residual nuclei are not exclusively formed by antiproton annihilation, but also from secondary interactions of the produced particles. Thus, an amount of residual nuclei is excpected to be formed outside the target. In order to estimate this amount, a calculation of the creation points of the positrons, based on nuclei deexcitation, is done and the results are shown in figure 4. Clearly can be seen the beam's path and the target region. The number of positrons created in the target is much higher than that produced outside the target and thus imaging of the irradiation beam should be feasible by detecting the 511keV produced photons.

3.2 Charged pions

Figures 5 illustrates the energy spectrum of charged pions which escape the phantom and thus are subjected to detection. Approximately 3 charged pions are produced per antiproton annihilation, so in total an enormous amount of pions is generated.

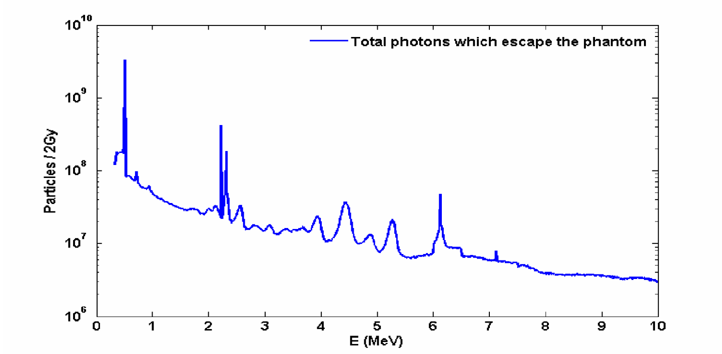

Figure 3. Energy spectrum of the photons which escape the phantom with energy going up to 10MeV. In this spectrum the 511keV peak is prominent. This peak is mainly constracted by the dexcitation of residual nuclei.

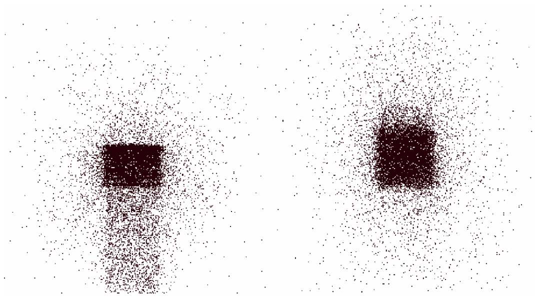

Figure 4. Points where beta+ particles are produced by the deexcitation of residual nuclei. Clearly the beam's path can be seen, the target allong the beam's axis (up) and the square field perpendicular to the beam (down). Many points are laid outside the target and this happens due to both the statistical phenomeno of the nuclear interactions and the fact that many residual nuclei are formed by interactions with particles which have been produced by antiproton annihilation. 10^6 antiprotons were used in order to constract the pictures.

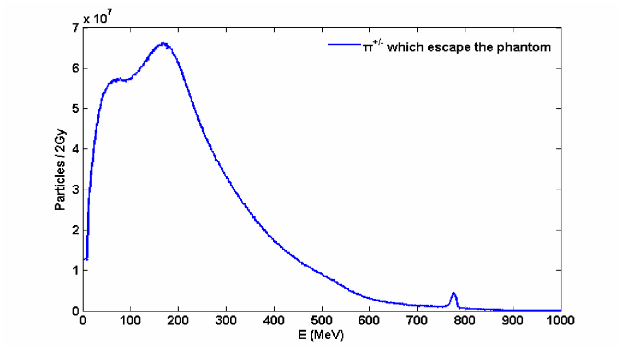

Figure 5. Energy spectrum of charged pions which escape the water phantom. About 20x10^9 $\pi^{+/-}$ escape the phantom when a 2Gy dose is delivered to the target, and are emitted in 4π geometry.

Charged pions undergo many scatters until they manage to escape the phantom. In order to study whether these pions are suitable for imaging, a calculation of the distance from their production point and the extrapolated point defined from the detection of pions outside the phantom, is

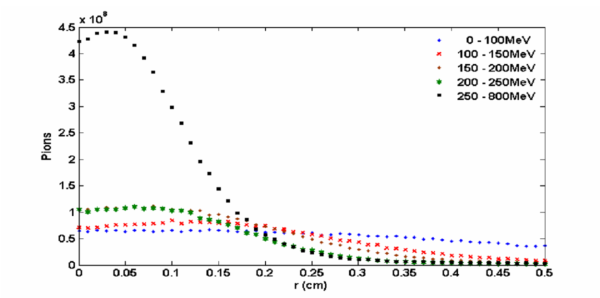

Figure 6. Distance distribution of the position where the charged pions are produced and the position where is extrapolated when they are detected at phantom's surface. Approximately 75% of $\pi^{+/-}$ desist less than 1mm when their kinetic energy varies from 250-800MeV. About 6.7x10^9 pions which escape the phantom have energy in this energy interval.

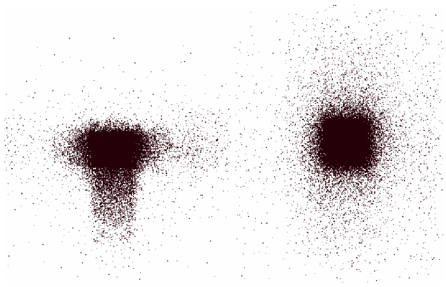

Figure 7. Points which are extrapolated when charged pions are being detected by the ring detector of figure 1. These pions have kinetic energy from 0-800MeV and the points have been reproduced when the line of the detected track of two or more charged pions is closer than 1mm distance. 10^6 antiprotons were used in order to constract the pictures.

done. As a criterion for the distinguish of proper and non-proper for imaging pions, depending on their energy, a value of 1mm is used as a criterion for the above distance, due to the fact that the new diagnostic techniques have also accuracy of the order of 1mm. Figure 6 shows the distance for different energy intervals. By detecting pions with 250-800MeV kinetic energy approximately the 75% of pions are detected in less than 1mm far from their production point. This energy interval containes about 6.7x10^9 $\pi^{+/-}$ when a 2Gy dose is delivered to the prostate. So, charged pions with kinetic energy higher than 250MeV are suitable for imaging.

Figures 7 and 8 illustrate the reconstracted images when charged pions are detected by the ring detector in figure 1. When an energy discrimination of pions does not occur, the image has muddily borders (figure 7), but when pions with kinetic energy higher than 250MeV are detected the borders are more distinct (figure 8).

4 Conclusions

In this study real time imaging with antiprotons was examined in detail. The study of both the energy spectra and the percentage of scattering of the particles produced when a 2Gy dose is delivered to the target lead us to the conclusion that real-time imaging is promising by detecting photons

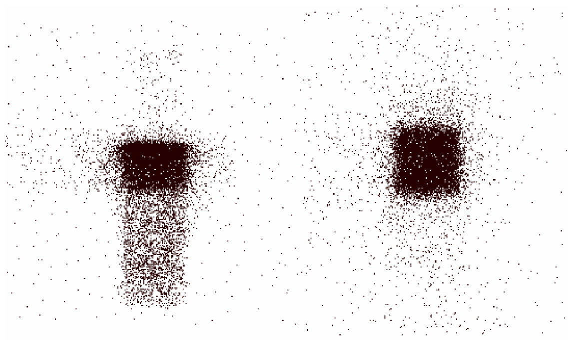

Figure 8. Points which are extrapolated when charged pions with kinetic energy higher than 250MeV are being detected by the ring detector of figure 1. The borders of the target are more evident in comparison with figure 7. This difference is due to the fact that in figure 8 only pions with kinetic energy higher than 250MeV are used contrary to figure 7 where all pions where used. 2x10^6 antiprotons were used in order to constract the pictures.

and especially those with 511keV energy with a PET camera. Only an experiment could prove if a real-time or a delay-time imaging is feasible.

On the other hand, we are confident that real-time imaging is feasible by detecting charged pions. It's easy to detect the track of a charged particle and then to extrapolate to the annihilation point. Moreover, using proper equipment in order to distinguish the charged particles with kinetic energies higher than 250MeV (e.g. by measuringdE/dx or by using an external magnetic field), instead of detecting all the charged particles, imaging with increased accuracy (of the order of 1mm) could be feasible.

Acknowledgments

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References

[1] L. Gray and T.E. Kalogeropoulos, *Possible biomedical applications of antiproton beams: focused radiation transfer*, *Radiat. Res.* **97** (1984) 246.

[2] T.E. Kalogeropoulos and R. Muratore, *Antiprotons for imaging and therapy*, *Nucl. Instrum. Meth.* **B 40/41** (1989) 1322.

[3] M.H. Holzscheiter et al., *The biological effectiveness of antiproton irradiation*, *Radiother Oncol.* **81** (2006) 233.

[4] A. Fasso' et al., *FLUKA: a multi-particle transport code*, CERN-2005-010 [SLAC-R-773].

[5] A. Fasso' et al., *The physics models of FLUKA: status and recent developments*, talk at the *Computing in High Energy and Nuclear Physics* 2003 *Conference (CHEP*2003*)*, March 24–28, La Jolla, U.S.A. (2003), `hep-ph/0306267`.

[6] C. Theis et al., *Interactive three dimensional visualization and creation of geometries for Monte Carlo calculations*, *Nucl. Instrum. Meth.* **A 562** (2006) 827.

[7] M.J. Berge et al., *XCOM: photon cross sections database*, http://physics.nist.gov/PhysRefData/Xcom/Text/XCOM.html.